ROBUST DESIGN ANALYSIS OF A GAS TURBINE COMPONENT

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ABSTRACT
System quality and reliability are becoming increasingly more important for maintaining market place competitiveness and customer satisfaction. The objective of this paper is to demonstrate the application of the Taguchi Method as a straightforward means of improving product quality using simulation based predictions of the operating life of a critical gas turbine component. The method is applied to statistically select a set of creep life simulations that will illuminate a bucket design which is least sensitive to component and operating environment variation. Implications of this method to improving turbine component quality at the design level are discussed. The results of the Taguchi Method are compared to a robust design solution found using the more time consuming, yet more accurate Response Surface Monte Carlo method. Apparent advantages and limitations of the Taguchi method as applied to turbine component design are discussed.

NOMENCLATURE

A, B, -Q/R creep life constants
b_o intercept term
b_i first-order regression coefficient for x_i
COV Coefficient of Variation
x_i independent parameter
b_a second-order regression coefficient
b_ij first-order interaction coefficient
i inner array index subscript
j outer array index subscript
m number of inner array control variable combinations
n number of outer array combinations
S bulk section stress (ksi)
S/N signal to noise ratio statistic
T bulk section temperature (Fahrenheit)
Y_i i^{th} outer array responses for control variable setting
μ mean of response
σ standard deviation of response

INTRODUCTION
The purpose of this paper is to demonstrate and evaluate how a robust design analysis of a gas turbine bucket with respect to its creep life can be achieved using the rather straightforward Taguchi Parameter Design method. A sophisticated multidisciplinary computer simulation of the creep life of an operational land-based gas turbine engine bucket was developed and implemented. The simulation environment allows for the variation of the external and internal heat transfer boundary conditions, solid material properties, as well as geometric properties. Each simulation requires a large amount of computational resources giving credence to using a method such as Taguchi robust design where only a limited number of trials are required.

To evaluate the result of the Taguchi robust design solution, a more recent approach called the Response Surface Method (RSM) was applied. The RSM method required many more executions of the computationally expensive bucket model; however, results in an accurate approximation of the creep life as a function of all the variables of interest. This functional approximation, or metamodel, of the creep life permits a full probabilistic analysis using Monte Carlo (MC) to
be conducted over numerous combinations of the control parameter ranges within an acceptable amount of time. Therefore, the combined RSM/MC method in affect can be used as a validation tool for the simpler Taguchi results obtained within this study.

This paper is organized as follows. First, a concise overview of Robust Design is given which describes the Taguchi Method and the Response Surface Method used to validate the Taguchi results. Next, the multidisciplinary creep life simulation environment of the turbine bucket component is described. Then, a significant portion of the paper is devoted to discussing how the Taguchi method was applied and the results produced. A comparison to results generated using the more accurate RSM method is included in this section as a means of validating the Taguchi results. Finally, conclusions are made highlighting the advantages and disadvantages of using the Taguchi method for turbine bucket robust design.

**ROBUST DESIGN**

Robust design can be defined as the process of finding an optimum setting of design factors that yield a superior design that is economical yet insensitive to variation in the product operating environment. The premise of robust design is improving product quality during product design when the engineer has the most control and flexibility with regards to performance and cost. Effectively, this amounts to a notable paradigm shift in quality improvement approaches which traditionally focused on process parameters subsequent to and uncoupled from the product design phase.

One widely used method of robust design is the Taguchi Method which was developed in the early 80’s under the direction of Dr. Genichi Taguchi\(^1\). The Taguchi method consciously considers both control and noise factors and the cost of failure in the field, therefore ensuring the greatest quality with minimum part-to-part variation. The method consists of three major steps: 1) system design, 2) parameter design, and 3) tolerance design.

System design is the integration and synthesis phase where the product is initially realized as a functioning component. Within this paper the system design step is assumed to have been completed with the availability of an existing baseline gas turbine bucket model. The baseline component design determined during the system design step then becomes the starting point for the subsequent step, parameter design.

Parameter design involves evaluating the product over specified ranges of the nominal parameter values and choosing the values that lead to the lowest sensitivity to operating variation. The last step, tolerance design, is executed only if parameter design fails to achieve an acceptable level of insensitivity to variation. This step involves reducing product and process tolerances which influence the product variation. Simply put, parameter design is where the designer can achieve the most improvements with regard to quality and cost while tolerance design, although necessary at times, results in elevated costs as a result of tightening product and process tolerances. Therefore, Taguchi parameter design is the focus of this study.

**Taguchi Parameter Design Method**

Parameter design is the core of the Taguchi Method. The objective of this step is to identify and vary both control and noise factors using a systematic approach. This provides a rudimentary quantification of their interaction called the signal to noise ratio which is used to allow for finding a robust setting of the control factors.

A signal factor is one that primarily affects the mean response of the performance characteristic. A control factor is defined as a factor that can be changed by the designer and is one that primarily affects the S/N ratio but not the mean. A noise factor, on the other hand, is one which is difficult or even impossible to control. Noise factors can be further classified into either outer, inner, or between-product noise. Outer noise is the noise external to the product in question, such as operating environment, while inner noise is the internal noise of the product such as material variability. Between product noise is the noise introduced by the manufacturing process.

Orthogonal arrays primarily at two or three levels are used to create a balanced and unbiased Design-Of-Experiments (DOE)\(^1\) using both the control and noise parameters. Two orthogonal arrays, an inner design array for the control parameters and an outer noise array for the noise parameters, are crossed as shown in Figure 1. For each combination of control variable settings, the experiment or simulation is repeated over all of the combinations of the noise variables. Thus, there are \(n\) performance characteristic evaluations corresponding to \(n\) combinations of the noise variable values for each of \(m\) settings of the control variables. The results from \(n\) combinations of the noise variables are then used to compute the \(mth\) performance statistic.

Taguchi proposed using the Signal-to-Noise ratio (S/N), leveraged from electrical engineering, to quantify the variation of the response at each level of control variable settings. The S/N ratio is simply a ratio of the mean (signal) to variation (noise). But, there are three forms of the S/N formula that are widely used to quantify such variation. The first form is used when the nominal or mean response is desired ("nominal-is-best") and is given as

\[
\frac{S}{N}_{\text{nominal-is-best}} = 10 \log_{10} \left( \frac{\mu^2}{\sigma^2} \right) \tag{1a}
\]

where

\[
\mu = \frac{1}{n} \sum_{i=1}^{n} Y_i \tag{1b}
\]

and

\[\sigma^2 = \frac{1}{n} \sum_{i=1}^{n} (Y_i - \mu)^2\]

\(^1\) Historically, Design-Of-Experiments (DOE) refers to actual physical tests of an object or device. In this study, DOE refers rather to computer simulations of a turbine bucket life analysis or design of simulations.
\[ \sigma^2 = \frac{1}{n-1} \sum_{i=1}^{n} (Y_i - \mu)^2 \]  

(1c)

When a smaller value of the response is desired ("smaller-is-better") the S/N ratio used is

\[ S / N_{\text{smaller-is-better}} = -10 \log_{10} \left[ \frac{1}{n} \sum_{i=1}^{n} Y_i^2 \right] \]

(2)

For the situation when the larger value of the response is desired ("larger-is-better") the following S/N formula is used

\[ S / N_{\text{larger-is-better}} = -10 \log_{10} \left[ \frac{1}{n} \sum_{i=1}^{n} \frac{1}{Y_i^2} \right] \]

(3)

The S/N ratio used depends on the situation, whether the nominal, smaller, or larger response value is desired. The combination of control variable values that are the least sensitive to noise is selected by finding those that yield the highest S/N ratio. Extended discussions of the Taguchi method have been conducted by Kacker (1985, 1986).  

\begin{tabular}{|c|c|c|c|c|}
\hline
\textbf{Control parameters} & \textbf{Noise factors} & \textbf{Performance characteristic} & \textbf{Performance statistic} \\
\hline
\textbf{Test runs} & \( \theta_1 \) & \( \theta_2 \) & \( \theta_3 \) & \( \theta_4 \) & \( w_1 \) & \( w_2 \) & \( w_3 \) & \( Y_i \) & \( [Z0]i \) \& \\
\hline
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & \( Y_1 \) & \( [Z0]1 \) \& \\
2 & 1 & 2 & 2 & 2 & 1 & 2 & 2 & \( Y_2 \) & \( [Z0]2 \) \& \\
3 & 1 & 3 & 3 & 3 & 1 & 3 & 3 & \( Y_3 \) & \( [Z0]3 \) \& \\
4 & 2 & 1 & 2 & 3 & 2 & 1 & 2 & \( Y_4 \) & \( [Z0]4 \) \& \\
5 & 2 & 2 & 3 & 1 & 2 & 2 & 1 & \( Y_5 \) & \( [Z0]5 \) \& \\
6 & 2 & 3 & 1 & 2 & 1 & 1 & 1 & \( Y_6 \) & \( [Z0]6 \) \& \\
7 & 3 & 1 & 3 & 2 & 1 & 2 & 2 & \( Y_7 \) & \( [Z0]7 \) \& \\
8 & 3 & 2 & 1 & 3 & 1 & 2 & 2 & \( Y_8 \) & \( [Z0]8 \) \& \\
9 & 3 & 3 & 2 & 1 & 1 & 1 & 1 & \( Y_9 \) & \( [Z0]9 \) \& \\
\hline
\end{tabular}

Figure 1: Taguchi Experiments for Parameter Design

**Response Surface Monte Carlo Method**

Validating any design solution, especially one that requires a probabilistic analysis such as the rudimentary one used in Taguchi, can be difficult. Testing actual buckets for each different design setting was far from practical for this study. Therefore, a simulation based approach was taken using the Response Surface (RSM) and Monte Carlo (MC) Method to validate the Taguchi results.

The RSM method determines an appropriate fit of a preconceived function about samples of a response to create an explicit functional representation of a more complex physical model. The Design-Of-Experiments method is employed to select an appropriate combination of variable settings to efficiently sample the actual response space. A more detailed description of DOE and RSM can be found in many previous publications. The RSM method is applied within this study to generate a closed-form, continuous functional representation of turbine bucket creep life as a function of several variables. The DOE used is a three level central composite design which permits the modeling of interactions between several of the main factors as well as quadratic main effects. Thus, a metamodel of the more time-consuming turbine bucket creep life analysis is created. A representative quadratic, polynomial metamodel commonly used is given as

\[ R = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{j=1}^{k} \sum_{j=1}^{k} b_{ij} x_i x_j + \epsilon \]

(4)

where the \( b_i \) are regression coefficients for the 1st degree terms, \( b_{ii} \) are the coefficients for the pure quadratic terms, \( b_{ij} \) are the coefficients for the cross-product terms, \( x_i, x_j \) are the design variables, \( x_i \) denotes first order interaction between two design variables, and \( \epsilon \) is the random error term of which its realizations are assumed to be independent and normally distributed with constant variance.

Probabilistic simulation analyses of the creep life requiring numerous evaluations of the bucket model are now highly feasible using the creep life metamodel. The probabilistic method chosen is the Monte Carlo simulation method (MC) which is the most general and most accurate probabilistic method given enough simulations. Where the Taguchi method requires only a few variations of the noise variables usually set at two levels, the Monte Carlo simulation technique can evaluate the response of interest at an extremely large number of noise variable values. Further, the Taguchi Method does not consider a continuous variation of the control variables whereas the RSM/MC method can model not only the variation of the control variables, but their underlying statistical distribution as well. Therefore, the combined RSM/MC method is considered an accurate probabilistic realization of the creep life of the component in question. This method requires at least a two fold increase in the number of actual creep life environment evaluations in addition to knowledge of Design-Of-Experiments and probabilistic analyses. A comparison of the two methods is given in addition to using this method to validate the Taguchi results.

**CREEP LIFE SIMULATION**

A sophisticated creep life simulation environment for a land-based, gas-turbine engine turbine bucket has been developed. The component selected, as shown in Figure 2, is a 2nd stage turbine bucket from a heavy-duty gas turbine. The bucket material is a cast, equiaxed nickel-based super-alloy. This particular bucket design includes eight radial cooling holes supplied by compressor bleed air.

Several mechanisms can contribute to the failure of such a component. Examples of such failure mechanisms include low cycle fatigue, creep, oxidation, overstress, and fatigue crack growth leading to fracture. For the purpose of demonstrating the Taguchi method, only the creep life response is considered and is done so in a section average sense at various airfoil sections of interest (see Figure 5).

The calculation of the bucket creep life requires the integration of numerous complex analyses using multiple variables. The structure of the analysis steps and data flow for the bucket creep life analysis is depicted in Figure 3. The
analyses parameterized by the environment are identified by the dashed line in Figure 3. They include a preliminary external boundary condition analysis, cooling-hole analysis, thermal solid analysis, mechanical analysis, and finally a creep life analysis. For the cooling hole analysis, a 1-D compressible-flow network solver is used to determine the internal heat transfer boundary conditions based on metal wall temperatures, flow passage geometric and frictional properties, and coolant flow properties. Recognizing that the metal wall temperature is an input to the coolant flow analysis and the internal heat transfer properties an input to the thermal solid analysis, a coupling routine was necessary. The coupling routine iterates between the coolant flow analysis and 3-D thermal solid analysis until the wall temperatures across the heat load surface converge. The wall temperatures are calculated using a steady-state, 3-D finite element thermal solid analysis.

Figure 2: 2nd Stage Turbine Bucket

A steady-state finite element thermal solid analysis is conducted to solve the thermal solid solution. The solution is repeated during the cooling hole coupling routine until a converged thermal solid solution is reached. A linearly-elastic steady-state mechanical analysis is conducted subsequent to the thermal solid solution using the thermal solution as input to the temperature-dependent material properties. Therefore, the thermo-mechanical results are obtained in an uncoupled fashion. However, the creep life is calculated as a function of both stress and temperature. The calculation of creep is desired at several sections along the bucket bucket. Section average solid temperatures (T) and stresses (S) in the radial direction were computed from the FEA solutions at eleven sections of interest, identified at 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 95% (see Figure 5).

The material creep life function used in this study is the Orr-Sherby-Dorn (OSD) three-term function based on the Arrhenius rate equation. The OSD creep life function computes the time to a specified amount of creep strain as a function of bulk section stress, $S$, and bulk section temperature, $T$, and is given as

$$t_{\text{creep}} = e^{\left(\frac{1}{A + B \ln S} - \frac{Q}{R} \right) \frac{T}{T}}$$

The parameters $A$, $B$, and $-Q/R$ are empirically determined creep constants corresponding to the time at which the accrual of a pre-defined amount of creep strain is reached. Several tests at various levels of stress and temperature must be performed to determine these creep-strain limit constants. They are unique both to the type of material used as well as the creep strain limit specified. Additional material characterization information for creep life modeling of nickel-based super alloys is given by Daleo et al.10,11 As a result, the creep life at each bucket cross-section of interest can be determined as a function of several upstream variables such as bucket external and internal heat transfer boundary conditions, material properties, geometry, and cooling passage frictional characteristics.

Figure 3: Generic Bucket Life Analysis Structure Matrix

An integrated computational environment called Automated Bucket Life Environment (ABLE) was developed to automate the creep life analysis. The environment, depicted in Figure 4, consists of a set of modular PERL scripts run by a single parent PERL script. Each child script automates one of the major analyses. Collectively, they orchestrate the passing of numerous input and output data files between each analysis. Several ANSYS Parametric Design Language (APDL) programs were written to automate the FEA steps including mapping of internal boundary conditions, the parameterization of the cooling-hole diameters, as well as the processing of the section temperatures, stresses, and finally the creep life calculation.
**Parameter Identification and Selection**

Initially, sixteen potential creep life variables were chosen based on engineering experience and judgement. Since over a dozen variables were identified, it was deemed necessary to reduce the number of variables under consideration. This was accomplished using a DOE screening study. A 2-level fractional factorial DOE was executed and the response for each case evaluated. Using Analysis of Variance (ANOVA), the relative contribution to the variation of creep life was quantified. The result of this step is shown in Figure 6. Notice that five variables were found to be the primary contributors to creep while the remaining variables were found to be relatively insignificant in terms of creep. These five variables contribute to more than 80% of the variation of creep life over the ranges of the sixteen variables initially considered.

The five primary variables include the external hot gas temperature field (SEXTT), the external heat transfer coefficient field (SEXTh), the creep constant variation parameter (CN), the friction factor multiplier for cooling holes 2 through 5 (SFM25), and the friction factor multiplier for cooling holes 6 through 8 (SFM68). The control variables SFM25 and SFM68 are scalar values that operate on a one-dimensional field of internal cooling hole friction factor values for cooling holes 2 through 5 and 6 through 8, respectively. The friction factor multiplier variable for the first cooling hole was determined through simulation to be insignificant for the range of the variables considered. SEXTTh and SEXTT are scalar values that represent a 3-D field of convective heat transfer coefficients and gas adiabatic wall temperatures for the external surface of the bucket, respectively. The CN parameter is an additional constant added to the exponential term in the creep life expression. This parameter represents a composite variation of the three creep constants, A, B, and –Q/R from equation 5. The appropriate range of each variable was also chosen using a combination of engineering judgement and available data. These five variables were then used for the robust design analysis using both the Taguchi and the RSM Method. The remaining variables were set to their expected, basing value.

![Figure 6: Pareto plot showing contributing creep life factors](image-url)
RESULTS

To apply the Taguchi method, each variable must first be defined as either a noise or a control variable. The variables SFM25 and SFM68 were defined as control variables. Although the bucket design under consideration is already in service, these two parameters were chosen as control variables since they are associated with the process used to produce the bucket. Other variables such as cooling hole diameters and locations, and the number of cooling holes are usually considered bucket design variables during the 'system' design phase and therefore weren't considered. Further, it is assumed for the purpose of this study that the frictional characteristics of cooling holes 2 through 8 can be controlled through process settings for the electro-chemical machining of the holes. In contrast, variables SEXTT and SEEXT are flow properties and are governed by the operating conditions of the engine. They are considered outside of the turbine bucket designer's control. Therefore, they were defined as noise variables. The creep constant variation term, CN, is a material property characteristic and is also fittingly classified as a noise variable.

In this particular problem, CN is considered an inner noise variable and SEXTT and SEEXT are outer noise variables. The next step is to decide on which variable settings from which to evaluate the creep life. This step is accomplished using the orthogonal array approach recommended by Taguchi.

The Taguchi orthogonal array experiments were determined by crossing the control (inner) and noise (outer) arrays each consisting of a two-level (high and low), full-factorial combination of each of the appropriate variables. The high low variable values were selected as the +/-1σ values for each of the five variables where the deviation was either quantified via test conditions or predicted by simulation or even expert judgment. The resulting coded combinations are given in Table 1. Area 1 is the design array and area 2 is the outer noise array. For each combination of the control variable settings, eight experiments or creep life simulations were conducted corresponding to each of the noise variable combinations. A four by eight matrix of creep life values, Yij, was produced.

The S/N ratio for all three situations, equations (1)-(3), were calculated for each of the control variable combinations and provided in Table 2. Since it is desirable to have the greatest creep life possible, the 'larger-is-better' S/N ratio, equation (3), was selected for finding the robust solution. According to the Taguchi approach, the case with the greatest S/N ratio (i.e. least sensitive to noise) is where both the control variables are set to their lowest value. The physical compliment to this solution would be to ensure that the wall surface frictional characteristics were reduced to their lowest setting. Reducing the frictional properties increases the coolant flow rate, thereby, increasing the cooling effectiveness resulting in a reduced metal temperature. Since creep is inversely proportional to the bucket metal temperature (equation 5), less friction results in both a deterministic and S/N ratio optimum for the creep life. Reduced friction has a physical affect of increasing the cooling flow rate. This reasoning must assume that the range of increased coolant flow doesn’t appreciably affect or penalize the gas path flow properties since the interaction between coolant flow rate and gas path flow rate isn’t modeled in this study.

Table 1: Taguchi Experiments

<table>
<thead>
<tr>
<th>CN</th>
<th>SEXTT</th>
<th>SEXTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>

Table 2: Taguchi Results

<table>
<thead>
<tr>
<th>Control Variables</th>
<th>Signal-to-noise ratio (S/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#</td>
<td>SFM25</td>
</tr>
<tr>
<td>1</td>
<td>1.4</td>
</tr>
<tr>
<td>2</td>
<td>1.4</td>
</tr>
<tr>
<td>3</td>
<td>0.6</td>
</tr>
<tr>
<td>4</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Validation using Response Surface and Monte Carlo

The RSM/MC method was applied to provide a reasonable validation of the Taguchi results generated within this study. A 43 case, central-composite DOE was conducted using the same ranges as those selected in the Taguchi analysis. The responses from the DOE provided the fitting points for the response surface approximation equation (RSE). The assumed RSE function was a quadratic, multivariate polynomial, which was generated through a least-squares fit from the creep life. However, fitting the quadratic function to the creep life directly produced an inferior fit due to the highly nonlinear nature of creep. Instead, the RSE was fit to the logarithm of bulk creep life which constituted a transformation of the response variable of interest. A near perfect correlation coefficient over the regression points was achieved with no more than 0.6% error all of the cases evaluated including over thirty randomly generated validation points (73 total points). In addition, the function was verified using several statistical techniques to ensure that the statistical model assumptions were met. The RSE was then used as a representation, or metamodel, of the complex physical model for large sample Monte Carlo analyses.

The Monte Carlo simulation technique was chosen to conduct the probabilistic creep life analysis of the 2nd stage turbine bucket using the creep life metamodel generated. The analysis consisted of choosing the distribution characteristics of the five primary random variables selected during the prior
screening study. The variable characteristics used are provided in Table 3. Each variable was assumed to be statistically independent and normally distributed. The baseline probability density function for the bucket creep life using the MC method is given by Figure 7. Notice that the creep life is log-normally distributed. More detailed results of the probabilistic analysis of this part can be found in the literature.

Table 3: Input Parameter Statistics

<table>
<thead>
<tr>
<th>Random Variable</th>
<th>Distribution</th>
<th>$\mu$</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>CN</td>
<td>normal</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>SEXTh</td>
<td>normal</td>
<td>nominal</td>
<td>5%</td>
</tr>
<tr>
<td>SEXTT</td>
<td>normal</td>
<td>nominal</td>
<td>0.77%</td>
</tr>
</tbody>
</table>

To validate the Taguchi results, separate Monte Carlo simulations such as the one shown in Figure 7 were conducted over an evenly spaced grid of the mean values of the two control variables, SFM25 and SFM68. For each combination of control variable mean values, 1E6 simulations were conducted. For each simulation, underlying variable statistics such as the variance of the two control variables and the mean and variance of the noise variables were all held constant. Thus, statistical raw data was generated using the MC method, which allowed for several robust quantities to be computed.

The ‘larger-is-better’ S/N ratio was computed using the raw MC simulation data for each of the control variable mean value combinations. The resulting contour plot of the S/N parameter as a function of the two control variables is shown in Figure 8. It is apparent that both the Taguchi and the RSM/MC results for the robust values of the control variables are in agreement. In addition, the deterministic optimum is equal to the robust optimum found using both the Taguchi and RSM/MC methods. Hence, from a designer’s perspective this scenario is the most ideal one. No compromises were required in order to find a solution that is simultaneously optimum with respect to maximizing the component creep life while minimizing its S/N ratio. However, the combination of control variable settings that would minimize solely the variation of creep life does not lie at the same point as the S/N and deterministic optimum. Taguchi suggests an inspection of both the mean and S/N ratio statistic but does not address the simultaneous consideration of both mean and variation of the response. Chen et al. have attempted to address this deficiency through the postulation of a numerical routine to simultaneously optimize both the variance and the mean value of a response of interest.

Figure 7: Baseline Life Probability Density Distribution

Figure 8: S/N Contour Plot Using RSE and Monte Carlo Simulation.

CONCLUSIONS

The Taguchi Parameter Design method utilized within this study has affectively found a robust design point using only 32 bucket creep life model evaluations. Following from the results of this study, it is recommended that the two control variables, cooling-hole friction factor multipliers, be reduced to their low value setting to yield both a maximum creep life and creep life S/N ratio. The Taguchi robust design point was validated by running several Monte Carlo probabilistic analyses using an accurate bucket creep life metamodel. Interestingly, the solution found using the less mathematically rigorous Taguchi method required less than half of the cases executed for the RSM method. Therefore, a Taguchi Parameter design analysis would be sufficient for the application described herein and especially appealing since each creep life simulation requires a few hours of computational time.

Yet, the Taguchi method is limiting in that it does not explicitly consider both the mean and variance separately. Further, this method retains no underlying statistical properties
of the variables of interest. For instance, should covariance and even non-normality exist amongst the uncertainty parameters then the resulting stochastic space could conceivably be much more irregular. Thus, the actual robust design point could not only be found at a corner point other than that predicted using Taguchi and even within the multidimensional input variable space between corner points. In addition, the S/N ratio used in Taguchi has additional limitations as emphasized by Parks (2001) such as: 1) Independent variable interactions cannot be modeled, 2) Limited to a single response, 3) Outer array matrix is cumbersome. The RSM/MC method overcomes these limitations by using an accurate metamodel, should one be realizable, coupled with the more general Monte Carlo probabilistic method. Thus, actual random variable characteristics can be quantified and modeled leading to tremendous flexibility for deterministic as well as non-deterministic activities.

It is important to note, however, that the orthogonal array cases conducted during the Taguchi method were the corner points of the higher level DOE used to create the creep life metamodel. A designer executing the RSM method can run these corner points first, apply the Taguchi method using these corner points within an inner/outer crossed matrix, and find a tentative robust design point while waiting for the remaining RSM DOE cases to be completed.

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